

Dependency of Compatibility Termination Criteria on Prehydration and Bentonite Quality for Geosynthetic Clay Liners

사전투수 및 벤토나이트 품질에 따른 GCL의 투수종결기준에 미치는 영향평가

Lee, Jae-Myung¹

이재명

Shackelford, Charles D.²

Choi, Jae-Soon³

최재순

Jung, Moon-Kyung⁴

정문경

요지

매립지나 오·폐수 저장지 등에서 폐기물 또는 오염물질의 저장 및 차단에 널리 사용되고 있는 Geosynthetic Clay Liner(GCL)의 물에 의한 사전투수 및 벤토나이트 품질이 투수종결기준에 미치는 영향을 평가하기 위해서 소듐 벤토나이트가 주성분인 두 종류의 GCL을 대상으로 증류수와 농도변화를 위해 5, 10, 20, 50, 100 mM 용액을 혼합한 염화칼슘용액을 이용하여 투수시험을 수행하였다. 투수종결기준들로는 물리적 종결기준들(즉, ASTM에 준한 유출량과 유입량간의 비율과 안정화된 투수계수, 최소 공극량 두배에 해당하는 유출, 그리고 안정화된 시료두께)과 유입수와 유출수간의 화학적 평형에 따른 화학적 종결기준들(즉, 전기전도도, pH, 그리고 칼슘 이온과 염소이온 농도)이 고려되었다. 염화칼슘을 이용한 투수시험의 경우, 벤토나이트에 이온결합된 나트륨(Na⁺)에 대한 칼슘(Ca²⁺) 치환이 GCL의 투수계수에 중대한 영향을 미치는 것에 근거하여 유입수와 유출수 간의 화학적 평형 및 투수계수의 평형이 이루어질 때까지 실시하였다. 염화칼슘농도에 따른 투수시험결과, 소요투수기간은 농도별로 1일 미만에서 900일 이상으로 큰 차이를 보였으며 염화칼슘 용액의 농도가 낮을수록 평형에 도달하기까지 더 많은 시간이 소요되는 것으로 나타났다. 특히, 염화칼슘 용액의 농도가 20 mM이하의 경우, GCL의 물에 의한 사전투수 여부와 벤토나이트의 품질에 상관없이 유입수와 유출수간의 화학적 평형만이 투수계수의 평형을 보장할 수 있는 것으로 나타났다. 그러나, 염화칼슘 용액의 농도가 50 그리고 100 mM의 경우, 유출량과 유입량간의 비율과 공극량 두배에 해당하는 유출을 제외한 모든 종결기준들이 투수계수의 평형을 보장할 수 있는 것으로 나타났다. 이상의 결과로부터, 물에 의한 사전투수 여부와 벤토나이트의 품질에 상관없이 오로지 유입수와 유출수간의 농도 평형에 준한 종결기준만이 GCL의 투수시험에 적합할 것으로 판단된다.

Abstract

The dependency of criteria used to terminate compatibility tests on the prehydration and quality of bentonite in geosynthetic clay liners (GCLs) is evaluated based on permeation with chemical solutions containing 5, 10, 20, 50, and 100 mM calcium chloride (CaCl₂). The hydraulic conductivity tests are not terminated before chemical equilibrium between the effluent and the influent chemistry has been established, resulting in test durations ranging from < 1 day to > 900 days, with longer test durations associated with lower CaCl₂ concentrations. The evaluation includes both physical termination criteria (i.e., volumetric flow ratio and steady hydraulic conductivity based on ASTM D 5084, ≥ 2 pore volumes of flow, constant thickness of specimen) and chemical termination criteria requiring equilibrium between influent and effluent chemistry (viz., electrical conductivity, pH, and Ca²⁺ and Cl⁻ concentrations). For specimens permeated with 5, 10, and 20 mM CaCl₂ solutions, only the criterion based on

1 Post-Doctoral Research Assistant, Dept. of Civil Engrg., Colorado State Univ.

2 Prof. and Director, EPA Rocky Mountain Regional Hazardous Substance Research Center (RMRHSRC), Dept. of Civil Engrg., Colorado Sate Univ.

3 Member, Post-Doctoral Research Assistant, Dept. of Civil Engrg., Yonsei Univ. (geocjs@yonsei.ac.kr)

4 Member, Senior Researcher, Korea Institute of Construction Technology (KICT)

chemical equilibrium in Ca^{2+} concentration correlates well with equilibrium in hydraulic conductivity, regardless of prehydration or quality of bentonite. However, all of the termination criteria, except for the volumetric flow ratio and 2 pore volumes of flow for the prehydrated specimens, correlate well with equilibrium in hydraulic conductivity regardless of prehydration or quality of bentonite when permeated with 50 and 100 mM CaCl_2 solutions. The results illustrate the uniqueness of the termination criterion based on solute concentration equilibrium between the effluent and the influent with respect to both prehydration and quality of bentonite in the GCLs.

Keywords : Bentonite quality, Chemical equilibrium, Geosynthetic clay liners, Hydraulic conductivity, Prehydration, Termination criteria

1. Introduction

The hydraulic conductivity of geosynthetic clay liners (GCLs) based on permeation with chemical solutions can be significantly higher than that based on permeation with water due to chemical interactions between the solutions and the bentonite (Daniel et al., 1993; Gleason et al., 1997; James et al., 1997; Petrov and Rowe 1997; Petrov et al., 1997a,b; Ruhl and Daniel 1997; Kolstad, 2000; Lin and Benson 2000; Shackelford et al., 2000; Egloffstein 2001; Jo et al., 2001; Vasko et al., 2001). The potential effect of a non-standard permeant liquid (i.e., liquid other than water) on the hydraulic conductivity of a clay barrier is usually assessed by permeating the clay barrier material with the actual liquid to be contained or, in the absence of the actual liquid, a simulated liquid with characteristics similar to those expected for the actual liquid. Since the primary objective of the test is to determine if the barrier material (e.g., bentonite in GCLs) and the permeant liquid are compatible, such that no significant change in hydraulic conductivity occurs, this type of test is often referred to as a compatibility test (Shackelford 1994; Shackelford et al., 2000).

In cases where GCLs have been permeated with solutions containing relatively low concentrations of polyvalent cations (i.e., < 50 mM), the GCLs typically have exhibited compatibility over relatively short durations (≤ 0.5 yr), but incompatibility after longer durations of permeation (> 1 yr) (Dobras and Elzea 1993; Didier and Comeaga 1997; James et al., 1997; Petrov and Rowe 1997; Ruhl and Daniel 1997; Kolstad 2000; Lin and

Benson 2000; Shackelford et al., 2000; Egloffstein 2001; Jo et al., 2001; Vasko et al., 2001). This apparent time-dependent compatibility of GCLs implies that the potential chemical interactions between the solutions and bentonites in the GCLs may not be complete within relatively short test durations when solutions containing polyvalent cations at relatively low concentrations (< 50 mM) are used as permeant liquids (Shackelford et al., 2000). For relatively high concentrations of polyvalent cations (i.e., ≥ 50 mM), several studies have shown significant increases in the hydraulic conductivity ($> 10X$) of GCLs over short test durations (Ruhl and Daniel 1997; Kolstad 2000; Shackelford et al., 2000; Egloffstein 2001; Jo et al., 2001; Vasko et al., 2001).

On the other hand, several investigators have reported that prehydration of bentonite mixtures and/or GCLs with water prior to permeation with actual permeant liquids can have a significant effect on hydraulic conductivity (Shan and Daniel 1991; Daniel et al., 1993; Shackelford 1994; Didier and Comeaga 1997; Gleason et al., 1997; Petrov and Rowe 1997; Petrov et al., 1997a; Quaranta et al., 1997; Ruhl and Daniel 1997; Stern and Shackelford 1998; Lin and Benson 2000; Shackelford et al., 2000; Vasko et al., 2001; Shan and Lai 2002). For example, the hydraulic conductivity of GCLs permeated directly with chemical solutions typically has been found to be significantly higher (i.e., $> 10X$) than the hydraulic conductivity of the same GCLs permeated with the same chemical solutions but after prehydration with water.

In addition, soil mixtures such as sand-bentonite mixtures that contain greater amounts of bentonite are

potentially more vulnerable to chemical attack and incompatibility than the mixtures with less amounts of bentonite (Stern and Shackelford 1998). Consequently, similar results for GCLs are expected such that the higher the quality of the bentonite (e.g., the higher the montmorillonite content) used in the GCL, the more vulnerable the GCL to chemical attack and, therefore, incompatibility, i.e., provided all other GCL properties (e.g., bentonite dosage) are the same (Shackelford et al., 2000).

As a result of the aforementioned considerations, the objective of this study is to evaluate the potential dependency of criteria commonly used to terminate laboratory compatibility tests on the prehydration and the quality of bentonite for GCLs permeated with CaCl_2 solutions. In order to achieve this objective, hydraulic conductivity tests are performed on both non-prehydrated and prehydrated specimens of a single GCL containing relatively low quality bentonite as well as non-prehydrated specimens of a different GCL containing relatively high quality bentonite. The tests are conducted until complete chemical equilibrium between the influent and effluent is established, which in some cases required in excess of 2 yrs of permeation. The results of this study should improve our understanding of appropriate termination criteria to be used for compatibility testing of GCLs.

2. Materials and Methods

2.1 Geosynthetic Clay Liners

Two geosynthetic clay liners (GCLs) containing bentonite with different montmorillonite contents were used in this study. Both GCLs consist of a thin layer of granular sodium bentonite sandwiched between two polypropylene geotextiles held together by needle-punched fibers. Both GCLs are 6-mm thick in the air-dried condition, and the average gravimetric water contents and specific gravity (ASTM D 854) of two bentonites are $4.0 \pm 1.0\%$ and 2.76 ± 0.02 , respectively. The GCL with the higher quality bentonite (GCL-HQB) is characterized by a greater content of sodium montmorillonite (86% vs. 77%), a higher plasticity index (548% vs. 393%), and a

higher cation exchange capacity (93 meq/100 g vs. 64 meq/100 g) relative to the GCL with the lower quality bentonite (GCL-LQB).

Particle-size distributions of the bentonite portions of the two GCLs were determined using both mechanical sieve analysis of the air-dried bentonite and hydrometer analysis (ASTM D 421, D 422). For both GCLs, the air-dried bentonite consists of more than 90% by dry weight (w/w) sand-sized granules (75 to 2000 μm) based on the mechanical sieve analyses, whereas approximately 90 % of particles are clay sized ($< 5 \mu\text{m}$) based on the hydrometer analyses. Consequently, the bentonites from both GCLs are classified as high plasticity clays (CH) according to the Unified Soil Classification System (ASTM D 2487) based on the wet analyses, whereas the results from the mechanical analyses indicate that the air-dried bentonites actually consist of assemblages or granules (i.e., clods) of individual clay particles and, therefore, are classified as poorly graded sand (SP). Shackelford et al. (2000) noted that GCLs containing granular bentonite might have significantly higher hydraulic conductivities relative to GCLs containing powdered bentonite upon direct permeation with non-standard liquids (i.e., liquids other than water). Further details of the physical and chemical properties and mineralogical compositions of the bentonites are given in Lee (2004) and Lee and Shackelford (2005b).

2.2 Permeant Liquids

The permeant liquids used in the experiment consist of tap water that is processed by passage through three ion exchange columns (Barnstead[®]) in series (pH ~ 5.6 , electrical conductivity, EC, at 25 $^{\circ}\text{C}$ ~ 0.2 mS/m) and solutions containing concentrations of calcium chloride (CaCl_2) ranging from 5 mM to 100 mM. The processed tap water is classified as Type IV deionized water (DIW) as per ASTM D 1193. Calcium chloride was chosen primarily because previous studies involving permeation of bentonite-based hydraulic barrier materials (e.g., GCLs, sand-bentonite mixtures) with CaCl_2 solutions have shown significant effects of the solutions on the

hydraulic conductivity of these materials (Alther et al., 1985; Daniel et al., 1993; Shackelford 1994; Imamura et al., 1996; Gleason et al., 1997; James et al., 1997; Melchior 1997; Quaranta et al., 1997; Ruhl and Daniel 1997; Kolstad 2000; Lin and Benson 2000; Shackelford et al., 2000; Egloffstein 2001; Jo et al., 2001; Vasko et al., 2001; Shan and Lai, 2002).

The CaCl₂ solutions were prepared by dissolving CaCl₂ (powdered, > 96% pure, Sigma-Aldrich Co., St. Louis, MO) in the DIW. Each solution was mixed in a 20-L carboy, and pH, EC, and solute concentrations of the permeant liquids were monitored with time using a pH meter (Accumet[®] AB15 meter, Fisher Scientific Co., Pittsburgh, PA), an EC probe (Accumet[®] AB30 meter, Fisher Scientific Co., Pittsburgh, PA), an ion chromatograph (Dionex[®] 4000i IC Module, Dionex Co., Sunnyvale, CA) for chloride (Cl⁻) concentrations, and an inductively coupled plasma - atomic emission spectrometer (IRIS[®] Advantage /1000 ICAP Spectrometer, Thermo Jarrell Ash Co., Franklin, MA) for calcium (Ca²⁺) concentrations, respectively. Further details on the measured properties of the permeant liquids are given in Lee (2004) and Lee and Shackelford (2005b).

2.3 Hydraulic Conductivity Tests

Specimens of the two GCLs with nominal diameters of 102 mm were permeated using the falling-head procedure and flexible-wall permeameters in accordance with ASTM D 5084. Hydraulic conductivity tests were performed on both non-prehydrated and prehydrated specimens of the GCL with the lower bentonite quality (i.e., GCL-LQB), as well as non-prehydrated specimens for the GCL with the higher bentonite quality (i.e., GCL-HQB). Prehydration was achieved by permeating the GCL specimens with DIW. The specimens were trimmed and assembled in the permeameters using the method described by Daniel et al. (1997) to prevent the possibility of short circuiting through the geotextiles at the edge of the GCL specimens due to loss of bentonite and pinching of the geotextiles. Backpressure was not used so that effluent liquids could be conveniently

collected for measuring pH, EC, and solute concentration. All the specimens were permeated at an average effective stress of ~ 23.5 kPa (3.4 psi) and at an average hydraulic gradient of 200. The hydraulic conductivity tests performed on non-prehydrated specimens using solutions with relatively high CaCl₂ concentrations (i.e., 50 and 100 mM) were duplicated because the test durations were relatively short, allowing for the re-use of the permeameters. However, because the durations for the tests using solutions containing relatively low CaCl₂ concentrations (i.e., 5, 10, and 20 mM) required more than 4 months to establish chemical equilibrium, these tests could not be duplicated due to the limited number of permeameters available for testing. Further details regarding the hydraulic conductivity testing are given elsewhere (Lee, 2004; Lee and Shackelford, 2005a,b).

Two categories of termination criteria commonly used for compatibility tests were considered in this study (Shackelford et al., 2000). The first category is referred to as physical termination criteria, and includes the following criteria: (1) at least four consecutive values for the ratio of the volumetric outflow to the volumetric inflow within the range of 1.00 ± 0.25 (e.g., ASTM D 5084); (2) at least four consecutive hydraulic conductivity (*k*) values within $\pm 25\%$ of the mean value for $k \geq 1 \times 10^{-8}$ cm/s or within $\pm 50\%$ of the mean value for $k < 1 \times 10^{-8}$ cm/s (e.g., ASTM D 5084); (3) a minimum of two pore volumes of flow (PVF) through the specimen (Bowders et al., 1986; Daniel 1994; Shackelford et al., 2000; ASTM D 6766); and (4) a constant thickness of the specimen (Petrov et al., 1997a). The second category of termination criteria relates to the need to establish chemical equilibrium between the effluent and influent (Bowders et al., 1986; Bowders and Daniel 1987; Bowders 1988; Daniel 1994; Shackelford 1994; Shackelford et al., 2000). This category, referred to as chemical termination criteria, includes the following criteria: (1) the ratio of effluent pH and EC relative to influent pH and EC within 1.00 ± 0.10 (Shackelford et al., 2000; ASTM D 6766); and (2) the ratio of effluent solutes concentration to influent solutes concentration within 1.00 ± 0.10 (Shackelford et al., 2000).

3. Results and Discussion

The results of all the hydraulic conductivity tests are summarized in Tables 1 and 2 in terms of the physical and chemical termination criteria evaluated in this study, respectively. The data upon which the results for both non-prehydrated and prehydrated specimens of the GCL with the lower quality bentonite (i.e., GCL-LQB) can be found in Lee and Shackelford (2005a), whereas the data upon which the results for the non-prehydrated specimens of both the GCL-LQB and the GCL with the higher quality bentonite (i.e., GCL-HQB) can be found in Lee and Shackelford (2005b). Although data upon which the results in Tables 1 and 2 are based have previously been reported, an analysis of the data within the context of the

current study has not previously been reported.

3.1 Inadequacy of pH Equilibrium

The test results indicated that the pH ratio (i.e., pH_{out}/pH_{in}) never reached the acceptable range (i.e., 1.00 ± 0.10) for all of the tests, except for one test performed on the prehydrated specimen with the 100 mM $CaCl_2$ solution (see Lee 2004). As a result, the termination criterion based on pH equilibrium was found not to be applicable in this study. The increased effluent pH relative to the influent pH (i.e., $pH_{out}/pH_{in} > 1.10$) was due, in part, to the buffering capacity of bentonite as well as the decrease in the influent pH due to time-dependent dissolution of carbon dioxide (CO_2). In addition, if the

Table 1. Summary of test results based on physical termination criteria.^a

Permeant Liquid	Test No.	GCL Type ^b	Pre-hydration	Slope of $k \sim 0^c$		Physical Termination Criteria							
						ASTM D 5084				2 PVF		Constant Thickness	
						Q Ratio		Steady k					
						PVF _{$\Delta k \sim 0$} [t _{$\Delta k \sim 0$}]	$k_{\Delta k \sim 0}$ (cm/s)	PVF ₀ [t ₀]	$k_0/k_{\Delta k \sim 0}$	PVF _k [t _k]	$k_k/k_{\Delta k \sim 0}$	[t _{2PVF}]	$k_{2PVF}/k_{\Delta k \sim 0}$
5 mM $CaCl_2$	1	LQB	No	54[494]	8.3×10^{-9}	1.5[5.5]	0.32	2.8 [25]	0.24	[15]	0.21	2.2[15]	0.21
	2	LQB	Yes	42[306]	8.0×10^{-9}	3.4[40]	0.29	3.4[40]	0.27	[31]	0.28	0.84[11]	0.26
	3	HQB	No	68[955]	1.8×10^{-8}	2.9[187]	0.04	2.2[150]	0.04	[150]	0.04	1.6[112]	0.04
10 mM $CaCl_2$	4	LQB	No	26[376]	6.8×10^{-9}	2.6[8.6]	0.37	3.9[36]	0.28	[2.5]	1.92	3.4[23]	0.28
	5	LQB	Yes	20[246]	6.1×10^{-9}	3.0[47]	0.48	3.0[47]	0.48	[36]	0.46	0.74[13]	0.40
	6	HQB	No	51[502]	1.7×10^{-8}	3.6[231]	0.04	4.4[254]	0.04	[169]	0.03	0.75[21]	0.06
20 mM $CaCl_2$	7	LQB	No	18[147]	9.5×10^{-9}	3.2[47]	0.15	3.9[59]	0.16	[34]	0.14	1.1[9.6]	0.28
	8	LQB	Yes	10[92]	9.3×10^{-9}	2.5[41]	0.37	2.5[41]	0.37	[41]	0.37	0.62[14]	0.21
	9	HQB	No	19[150]	1.7×10^{-8}	3.1[48]	0.06	4.5[90]	0.07	[25]	0.09	2.0[25]	0.09
50 mM $CaCl_2$	10	LQB	No	7.0[12]	1.6×10^{-8}	3.0[5.6]	0.85	3.0[5.6]	0.85	[4.2]	0.80	1.5[2.7]	0.83
	11	LQB	No	4.8[8.9]	1.8×10^{-8}	2.7[5.5]	0.86	2.7[5.5]	0.86	[4.2]	0.81	1.3[2.6]	0.83
	12	LQB	Yes	11[25]	3.5×10^{-8}	3.0[15]	0.43	6.5[20]	0.88	[15]	0.43	6.5[20]	0.88
	13	HQB	No	24[0.13]	4.8×10^{-6}	3.4[0.021]	0.53	4.3[0.027]	0.57	[0.014]	0.54	5.3[0.033]	0.62
	14	HQB	No	18[0.18]	3.7×10^{-6}	2.9[0.035]	0.46	3.6[0.046]	0.54	[0.024]	0.52	2.9[0.035]	0.46
100 mM $CaCl_2$	15	LQB	No	9.1[0.98]	3.4×10^{-7}	3.0[0.39]	0.58	3.0[0.39]	0.58	[0.29]	0.59	1.5[0.19]	0.69
	16	LQB	No	5.3[0.54]	3.5×10^{-7}	3.0[0.37]	0.89	3.7[0.43]	0.83	[0.31]	0.82	0.75[0.15]	0.38
	17	LQB	Yes	14[11]	1.2×10^{-7}	3.4[8.5]	0.54	6.8[9.5]	0.72	[8.1]	0.21	6.8[9.5]	0.84
	18	HQB	No	19[0.015]	3.4×10^{-5}	2.9[0.003]	0.84	2.9[0.003]	0.84	[0.002]	0.76	4.6[0.004]	0.89
	19	HQB	No	22[0.012]	4.2×10^{-5}	3.6[0.002]	0.71	3.6[0.002]	0.71	[0.002]	0.67	2.7[0.002]	0.67

^a k = hydraulic conductivity; Q = volumetric flow rate; PVF = pore volumes of flow; t = elapsed time in days, respectively.

^b LQB = GCL with lower quality bentonite; HQB = GCL with higher quality bentonite, respectively.

^c When the slope of k versus number of PVF is statistically zero (Peirce and Witter 1986).

Table 2. Summary of test results based on chemical termination criteria.^a

Per-meant Liquid	Test No.	GCL Type ^b	Pre-hydrat-ion	$k_{\Delta k \sim 0}^c$ (cm/s)	Chemical Termination Criteria							
					EC Ratio ^d				C _{Cl} Ratio ^d (1.00 ± 0.10)		C _{Ca} Ratio ^d (1.00 ± 0.10)	
					(1.00 ± 0.10)		(1.00 ± 0.05)		PVF _{C_{Cl}0.1} [t _{C_{Cl}0.1}]	k _{C_{Cl}0.1} /k _{Δk~0}	PVF _{C_{Ca}0.1} [t _{C_{Ca}0.1}]	k _{C_{Ca}0.1} /k _{Δk~0}
					PVF _{EC0.1} [t _{EC0.1}]	k _{EC0.1} /k _{Δk~0}	PVF _{EC0.05} [t _{EC0.05}]	k _{EC0.05} /k _{Δk~0}				
5 mM CaCl ₂	1	LQB	No	8.3 x 10 ⁻⁹	24[338]	0.26	32[403]	0.39	6.3[80]	0.18	57[502]	1.04
	2	LQB	Yes	8.0 x 10 ⁻⁹	4.2[51]	0.28	16[174]	0.34	2.5[31]	0.28	58[358]	0.98
	3	HQB	No	1.8 x 10 ⁻⁸	16[632]	0.10	20[721]	0.11	4.2[256]	0.04	58[934]	0.93
10 mM CaCl ₂	4	LQB	No	6.8 x 10 ⁻⁹	14[280]	0.30	20[341]	0.64	11[234]	0.22	30[397]	0.98
	5	LQB	Yes	6.1 x 10 ⁻⁹	3.0[47]	0.48	3.8[60]	0.43	3.0[47]	0.48	35[360]	1.02
	6	HQB	No	1.7 x 10 ⁻⁸	16[422]	0.23	18[435]	0.32	4.4[254]	0.05	60[515]	1.02
20 mM CaCl ₂	7	LQB	No	9.5 x 10 ⁻⁹	4.6[70]	0.17	12[127]	0.61	1.8[21]	0.17	31[178]	0.99
	8	LQB	Yes	9.3 x 10 ⁻⁹	3.2[49]	0.43	4.5[60]	0.55	1.9[34]	0.31	16[120]	0.94
	9	HQB	No	1.7 x 10 ⁻⁸	11[131]	0.59	27[164]	1.03	3.1[48]	0.06	22[154]	1.07
50 mM CaCl ₂	10	LQB	No	1.6 x 10 ⁻⁸	3.0[5.6]	0.85	3.8[7.0]	0.91	2.2[4.2]	0.80	9.3[16]	1.03
	11	LQB	No	1.8 x 10 ⁻⁸	2.7[5.5]	0.86	3.4[6.6]	0.91	2.0[4.2]	0.81	8.9[15]	1.06
	12	LQB	Yes	3.5 x 10 ⁻⁸	6.5[20]	0.88	7.9[21]	0.96	7.2[21]	0.91	11[24]	0.99
	13	HQB	No	4.8 x 10 ⁻⁶	4.3[0.027]	0.59	6.1[0.039]	0.63	2.5[0.014]	0.54	18[0.11]	0.97
	14	HQB	No	3.7 x 10 ⁻⁶	3.6[0.046]	0.50	5.1[0.065]	0.61	3.6[0.046]	0.50	17[0.18]	0.98
100 mM CaCl ₂	15	LQB	No	3.4 x 10 ⁻⁷	3.0[0.39]	0.58	3.8[0.48]	0.62	2.3[0.29]	0.59	6.8[0.80]	0.87
	16	LQB	No	3.5 x 10 ⁻⁷	2.2[0.31]	0.82	3.7[0.43]	0.96	1.5[0.24]	0.65	6.0[0.59]	1.07
	17	LQB	Yes	1.2 x 10 ⁻⁷	5.9[9.3]	0.78	9.3[10]	0.91	7.6[9.7]	0.86	10[10]	0.92
	18	HQB	No	3.4 x 10 ⁻⁵	2.1[0.002]	0.76	3.8[0.003]	0.88	1.4[0.001]	0.76	4.6[0.004]	0.89
	19	HQB	No	4.2 x 10 ⁻⁵	2.7[0.002]	0.67	4.5[0.003]	0.73	1.8[0.001]	0.73	11[0.006]	0.93

^a k = hydraulic conductivity; PVF = pore volumes of flow; t = elapsed time in days, respectively.

^b LQB = GCL with lower quality bentonite; HQB = GCL with higher quality bentonite, respectively.

^c When the slope of k versus number of PVF is statistically zero (Peirce and Witter 1986).

^d EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium; Ratio = effluent relative to influent, respectively.

liquid accumulated in the effluent reservoir is open to the atmosphere, then the release of aqueous-phase carbon dioxide (CO_{2(aq)}) into the atmosphere will result in a continual increase in the effluent pH with time (Shackelford 1994). Also, in closed systems such as the flexible-wall apparatus used in this study, the concentration of the CO_{2(aq)} in the pore liquid of a soil likely increases due to respiration by microorganisms under anaerobic conditions (Shackelford 1994). As a result, a pH increase in the effluent is expected due to release of CO_{2(aq)} as equilibrium with the atmosphere is established.

3.2 Equilibrium in Hydraulic Conductivity

In general, all of the hydraulic conductivity values for

the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions increased by 3.5X to 20X after > 10 PVF (0.3 yr) of permeation depending on prehydration condition and quality of bentonite in the GCLs, and then appear to stabilize. To determine equilibrium in hydraulic conductivity, the slope of hydraulic conductivity versus number of PVF was analyzed statistically using linear regression based on the t-test at a 5% significance level as described in Peirce and Witter (1986). The statistically zero slope of hydraulic conductivity was evaluated through analyzing the slope of five successive hydraulic conductivity values in series.

However, all of the hydraulic conductivity values for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions initially appear to stabilize within 10 PVF, and

then begin to increase. As a result, the achievement of statistically zero slope in hydraulic conductivity (hereafter referred to as “zero slope”) was considered valid only after the initial stage of the compatibility tests, particularly for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions. Even though the statistical approach is useful to determine the establishment of equilibrium in hydraulic conductivity, the statistical approach is meaningful only in conjunction with knowledge of the mechanisms involved in the compatibility tests (Bowders 1988).

3.3 Effect of Prehydration on Termination Criteria

The test results based on the physical termination criteria, including volumetric flow ratio and steady hydraulic conductivity per ASTM D 5084, 2 pore volumes of flow (PVF), and constant thickness of specimen as

well as the chemical termination criteria, including electrical conductivity (EC) and solutes (i.e., Cl⁻ and Ca²⁺) concentration equilibrium, are summarized in Tables 1 and 2, respectively. In addition, the hydraulic conductivity values based on each physical termination criterion are compared with those at the zero slope (or $k_{\Delta k \sim 0}$) for both non-prehydrated and prehydrated specimens of the GCL with the lower quality bentonite (i.e., GCL-LQB) in Fig. 1.

The hydraulic conductivity values based on the volumetric flow ratio per ASTM D 5084 (i.e., k_Q) are always from 2X to 7X lower than the $k_{\Delta k \sim 0}$ values regardless of prehydration for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions. In the case of the termination criterion based on the steady hydraulic conductivity per ASTM D 5084 (i.e., k_k), the hydraulic conductivity ratios (i.e., $k_k/k_{\Delta k \sim 0}$) for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions are always less than 0.5 regardless of prehydration. Similarly,

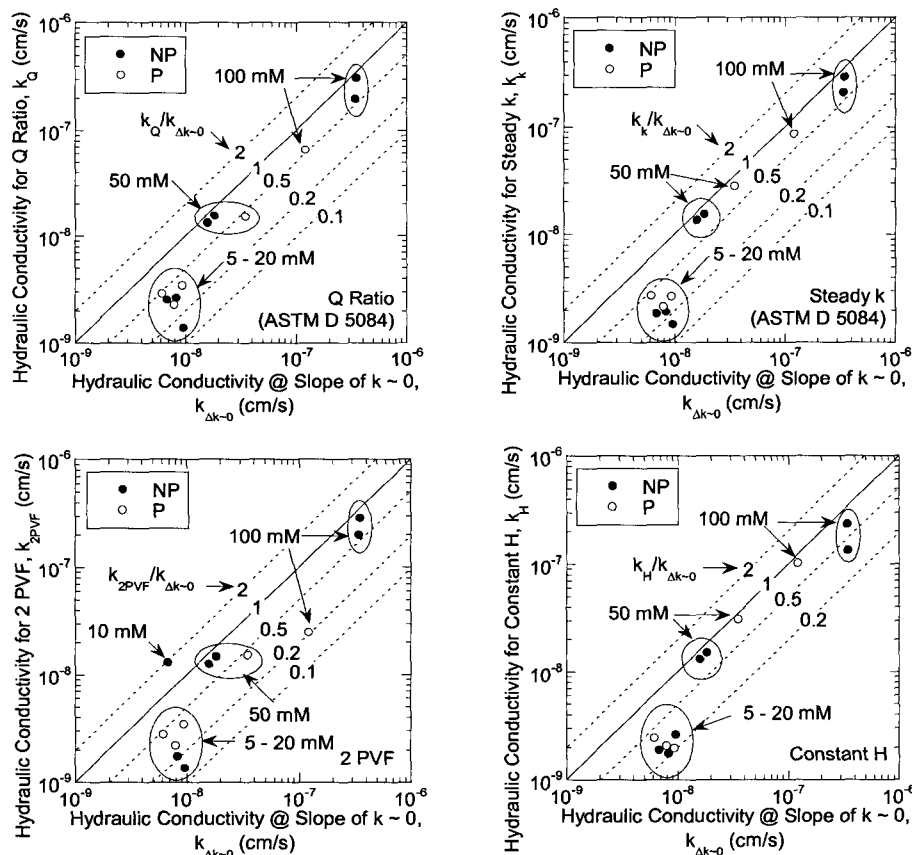


Fig. 1. Hydraulic conductivity for physical termination criteria versus hydraulic conductivity at the slope of $k \sim 0$ for both non-prehydrated (NP) and prehydrated (P) specimens of GCL with lower quality bentonite (Q = volumetric flow rate; PVF = pore volumes of flow; H = thickness of specimen)

the hydraulic conductivity ratios based on 2 PVF (i.e., $k_{2PVF}/k_{\Delta k \sim 0}$) are between 0.1 and 0.5 except for one test performed with the 10 mM CaCl₂ solution. In addition, the hydraulic conductivity values based on the constant thickness of specimens (k_H) are from 2X to 5X lower than the $k_{\Delta k \sim 0}$ values. Thus, none of physical termination criteria appears to be adequate regardless of prehydration for the specimens of GCL-LQB permeated with 5, 10, and 20 mM CaCl₂ solutions.

For the specimens permeated with 50 and 100 mM CaCl₂ solutions, the hydraulic conductivity values based on all of the physical termination criteria are not significantly lower (i.e., $\leq 31\%$) than the $k_{\Delta k \sim 0}$ values regardless of prehydration. However, the hydraulic conductivity values based on one single physical criterion (e.g., 2 PVF) for the prehydrated specimens are as much as 5X lower than the $k_{\Delta k \sim 0}$ values, whereas the hydraulic conductivity values based on any one of the physical criteria for the non-prehydrated specimens are not significantly lower (i.e., $< 45\%$) than the $k_{\Delta k \sim 0}$ values (see Fig. 1). Thus, any physical termination criterion appears to be adequate for the non-prehydrated specimens permeated with the 50 and 100 mM CaCl₂ solutions, whereas all of the physical termination criteria should be met for the prehydrated specimens to ensure equilibrium in hydraulic conductivity. This difference results from the need to displace the initial pore liquid (i.e., water) with the CaCl₂ solution for the prehydrated specimens and the subsequent chemical interactions that occur between the solution and the bentonite in the specimens. In fact, as shown in Fig. 1, the termination criterion based on the steady hydraulic conductivity per ASTM D 5084 tends to be the most appropriate in this study among the physical termination criteria for the prehydrated specimens of the GCL-LQB permeated with the 50 and 100 mM CaCl₂ solutions.

The hydraulic conductivity values based on the chemical termination criteria are compared with the $k_{\Delta k \sim 0}$ values for both non-prehydrated and prehydrated specimens of GCL-LQB in Fig. 2. Two limiting tolerances on EC equilibrium were considered to evaluate the effect of a more restrictive tolerance of $EC_{out}/EC_{in} = 1.00 \pm 0.05$

relative to the more commonly imposed tolerance of $EC_{out}/EC_{in} = 1.00 \pm 0.10$ (e.g., ASTM D 6766).

As shown in Fig. 2, the hydraulic conductivity values based on either EC tolerance generally are always lower than the $k_{\Delta k \sim 0}$ values regardless of prehydration for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions. In fact, the hydraulic conductivity ratios based on the EC ratio of 1.00 ± 0.10 (i.e., $k_{EC0.1}/k_{\Delta k \sim 0}$) are approximately 0.2 for the non-prehydrated specimens and 0.4 for the prehydrated specimens, whereas the hydraulic conductivity ratios based on the EC ratio of 1.00 ± 0.05 (i.e., $k_{EC0.05}/k_{\Delta k \sim 0}$) are about 0.5 for both non-prehydrated and prehydrated specimens. On the other hand, for the specimens permeated with 50 and 100 mM CaCl₂ solutions, the hydraulic conductivity values based on both ranges of the EC ratio are close to the $k_{\Delta k \sim 0}$ values (i.e., $0.78 \leq k_{EC0.1}/k_{\Delta k \sim 0} \leq 0.88$ and $0.91 \leq k_{EC0.05}/k_{\Delta k \sim 0} \leq 0.96$), except for one of the duplicate non-prehydrated specimens permeated with the 100 mM CaCl₂ solution, where the $k_{EC0.1}/k_{\Delta k \sim 0}$ and $k_{EC0.05}/k_{\Delta k \sim 0}$ values are 0.58 and 0.62, respectively. Thus, establishment of equilibrium in EC between effluent and influent is not sufficient to ensure equilibrium in hydraulic conductivity for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions regardless of prehydration, whereas the establishment of EC equilibrium tends to ensure hydraulic conductivity equilibrium for the specimens permeated with 50 and 100 mM CaCl₂ solutions.

As shown in Fig. 2, the hydraulic conductivity values based on equilibrium in chloride ($C_{Cl,out}/C_{Cl,in} = 1.00 \pm 0.10$) are always less than the $k_{\Delta k \sim 0}$ values for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions. In fact, the hydraulic conductivity ratios (i.e., $k_{Cl0.1}/k_{\Delta k \sim 0}$) based on the chloride (Cl⁻) concentration equilibrium are 0.2 for the non-prehydrated specimens and 0.4 for the prehydrated specimens. Thus, equilibrium in Cl⁻ concentration is not sufficient to ensure the achievement of equilibrium in hydraulic conductivity for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions, regardless of prehydration. However, as shown in Fig. 2, the hydraulic conductivity at zero slope (or $k_{\Delta k \sim 0}$) and hydraulic conductivity based on the Ca²⁺

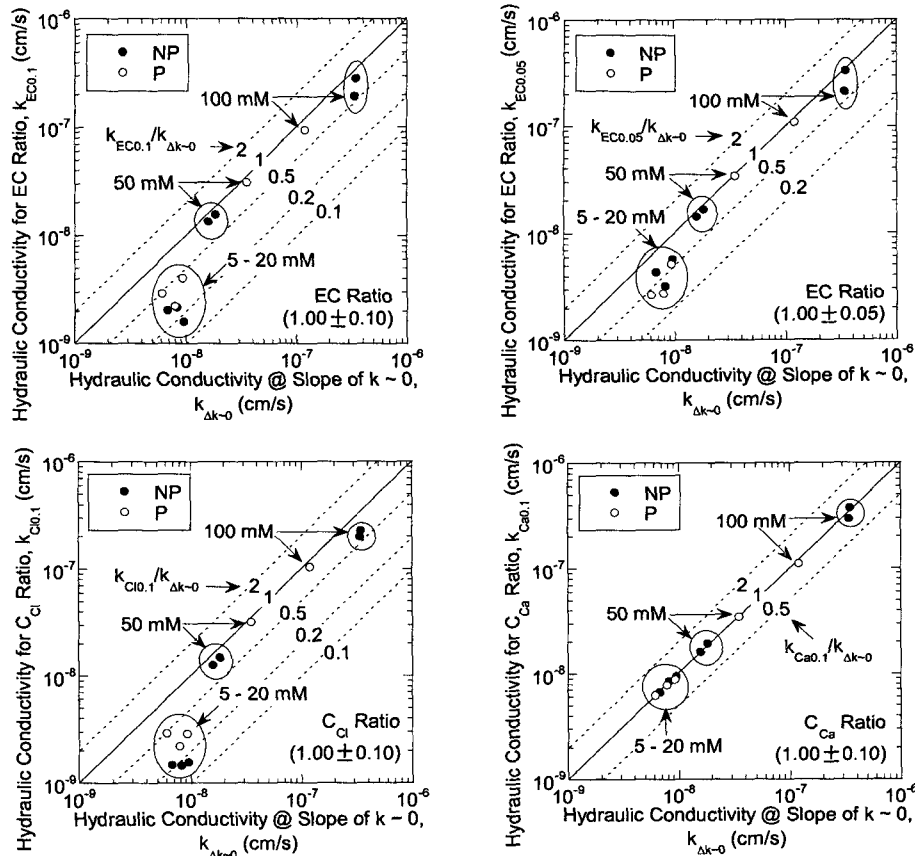


Fig. 2. Hydraulic conductivity for chemical termination criteria versus hydraulic conductivity at the slope of $k \sim 0$ for both non-prehydrated (NP) and prehydrated (P) specimens of GCL with lower quality bentonite (EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium)

concentration equilibrium are very close (i.e., $0.94 \leq k_{Ca0.1}/k_{\Delta k \sim 0} \leq 1.04$), supporting the applicability of salt cation concentration equilibrium as a necessary termination criterion for the specimens permeated with 5, 10, and 20 mM $CaCl_2$ solutions, regardless of prehydration. For the specimens permeated with the 50 and 100 mM $CaCl_2$ solutions, the hydraulic conductivity values based on either Cl^- or Ca^{2+} concentration equilibrium are not significantly different from the $k_{\Delta k \sim 0}$ values (i.e., $0.59 \leq k_{Cl0.1}/k_{\Delta k \sim 0} \leq 0.91$ and $0.87 \leq k_{Ca0.1}/k_{\Delta k \sim 0} \leq 1.06$).

The elapsed time and PVF required to reach each termination criterion are compared with those at the zero slope in Figs. 3 to 6. For example, the elapsed time required to achieve steady hydraulic conductivity per ASTM D 5084 was 2X to 20X lower than the elapsed time required to achieve $k_{\Delta k \sim 0}$ for the specimens permeated with 5, 10, and 20 mM $CaCl_2$ solutions. Similarly, the required PVF based on the same criterion

was still less than 5 PVF for the specimens permeated with 5, 10, and 20 mM $CaCl_2$ solutions. In other words, significantly more PVF (10 to 73 more) are required to achieve $k_{\Delta k \sim 0}$ than are required to meet the physical termination criteria. In fact, the overall physical termination criteria required 3 PVF, representing 40 days of permeation, for both non-prehydrated and prehydrated specimens of GCL-LQB permeated with 5, 10, and 20 mM $CaCl_2$ solutions, whereas ≥ 18 PVF for the non-prehydrated specimens and a minimum of 10 PVF for the prehydrated specimens are required to achieve the $k_{\Delta k \sim 0}$. For the specimens permeated with 50 and 100 mM $CaCl_2$ solutions, the elapsed time and PVF required to achieve each criterion as well as $k_{\Delta k \sim 0}$ generally are greater for the prehydrated specimens than for the non-prehydrated specimens.

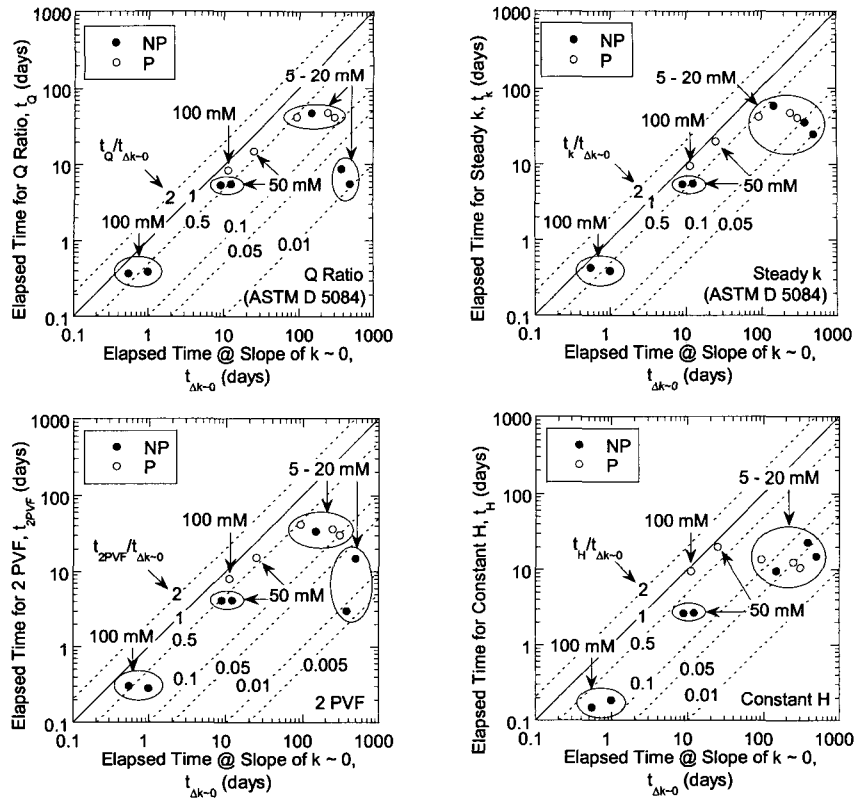


Fig. 3. Elapsed time for physical termination criteria versus elapsed time at the slope of hydraulic conductivity ~ 0 for both non-prehydrated (NP) and prehydrated (P) specimens of GCL with lower quality bentonite (Q = volumetric flow rate; PVF = pore volumes of flow; H = thickness of specimen)

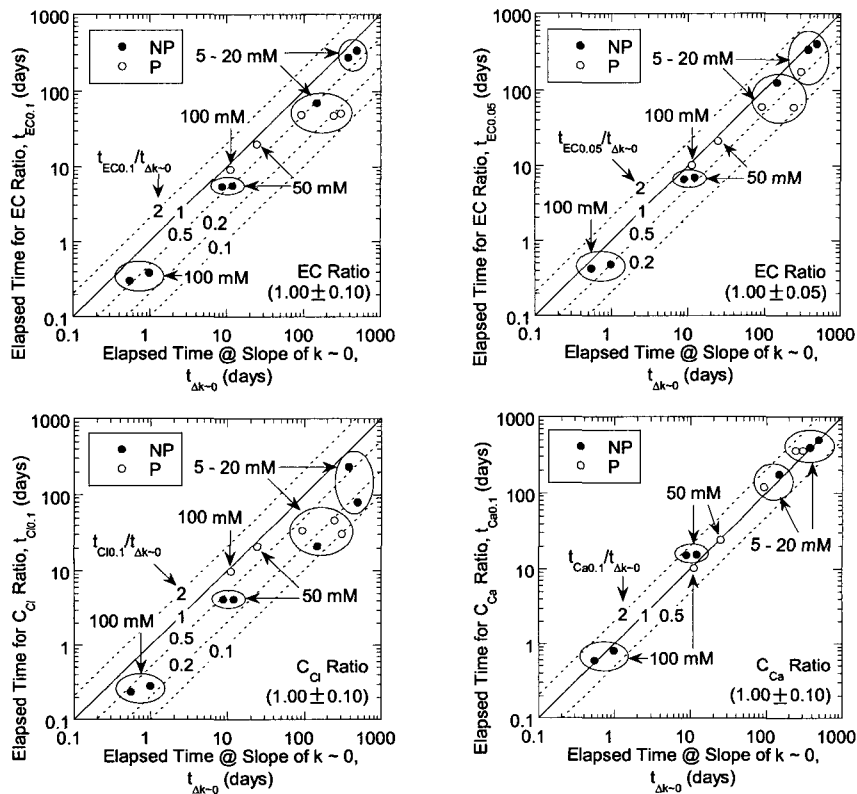


Fig. 4. Elapsed time for chemical termination criteria versus elapsed time at the slope of hydraulic conductivity ~ 0 for both non-prehydrated (NP) and prehydrated (P) specimens of GCL with lower quality bentonite (EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium)

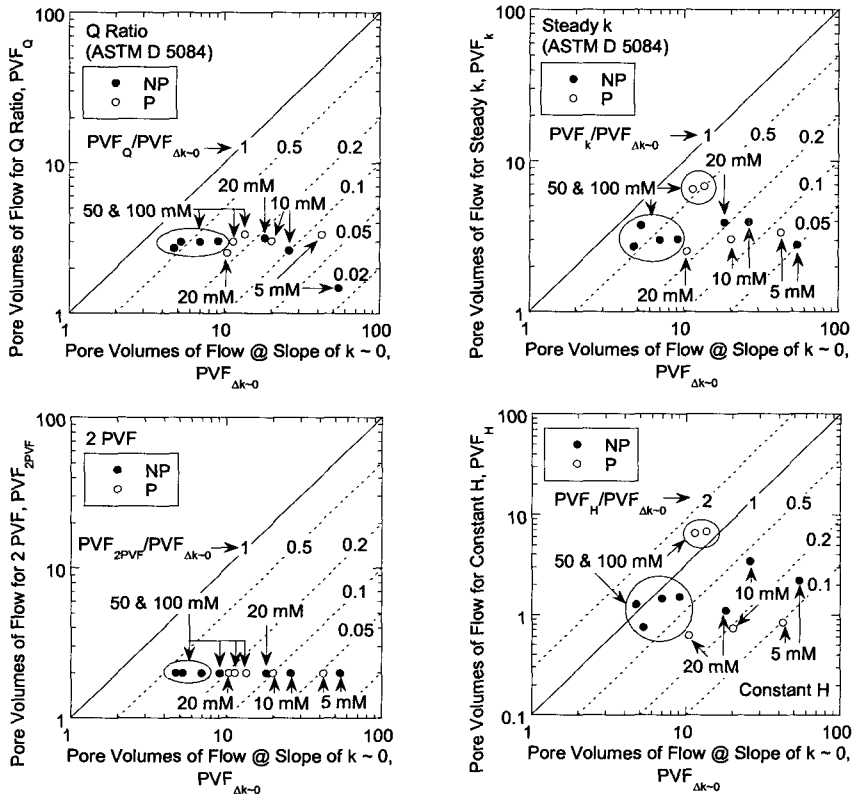


Fig. 5. Pore volumes of flow (PVF) for physical termination criteria versus PVF at the slope of hydraulic conductivity ~ 0 for both non-prehydrated (NP) and prehydrated (P) specimens of GCL with lower quality bentonite (Q = volumetric flow rate; H = thickness of specimen)

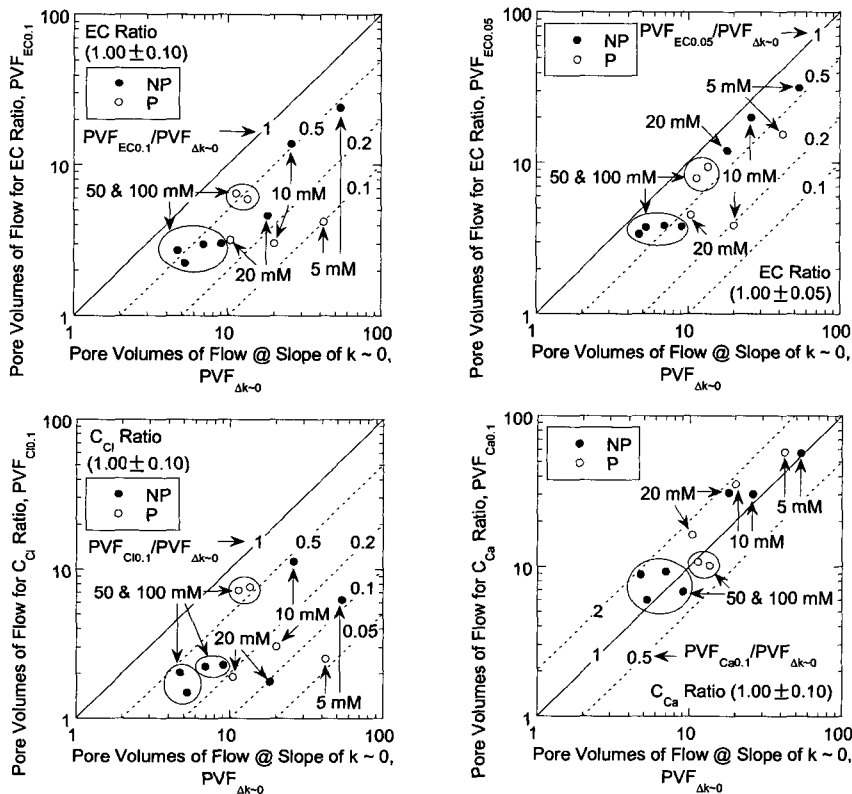


Fig. 6. Pore volumes of flow (PVF) for chemical termination criteria versus PVF at the slope of hydraulic conductivity ~ 0 for both non-prehydrated (NP) and prehydrated (P) specimens of GCL with lower quality bentonite (EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium)

3.4 Effect of Bentonite Quality on Termination Criteria

The hydraulic conductivity values based on each physical termination criterion are compared with the $k_{\Delta k \sim 0}$ values for the non-prehydrated specimens of the two GCLs with the lower quality bentonite (GCL-LQB) and the higher quality bentonite (GCL-HQB) in Fig. 7. The hydraulic conductivity values based on the volumetric flow ratio per ASTM D 5084 (k_Q) are always lower than $k_{\Delta k \sim 0}$ by a factor of 2.7X to 6.7X for the GCL-LQB and by a factor of 17X to 25X for the GCL-HQB. Thus, this termination criterion is inadequate in representing $k_{\Delta k \sim 0}$ regardless of bentonite quality for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions. For these tests, the elapsed time and PVF required to achieve $k_{\Delta k \sim 0}$ as shown in Figs. 8 and 9, respectively, are significantly greater (i.e., > 3 months and > 14 PVF) than those needed to meet the requirement for the volumetric flow ratio, regardless of the quality of bentonite used in the

GCLs. In the case of the termination criterion based on the steady hydraulic conductivity per ASTM D 5084, the hydraulic conductivity ratios (i.e., $k_k/k_{\Delta k \sim 0}$) for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions are always less than 0.3 for the GCL-LQB and less than 0.1 for the GCL-HQB, also indicating the inadequacy of this termination criterion regardless of bentonite quality.

Similarly, the hydraulic conductivity ratios based on the minimum requirement of 2 PVF (i.e., $k_{2PVF}/k_{\Delta k \sim 0}$) are 0.2 for the GCL-LQB and 0.05 for the GCL-HQB except for the specimen of GCL-LQB permeated with 10 mM CaCl_2 solution, in which the $k_{2PVF}/k_{\Delta k \sim 0}$ value is 1.9 due to relatively high hydraulic conductivity values at the beginning of the test. Thus, the termination criterion for steady hydraulic conductivity based on ASTM D 5084 is insufficient for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions regardless of bentonite quality. In addition, the hydraulic conductivity values based on the constant thickness of specimens (i.e., k_H)

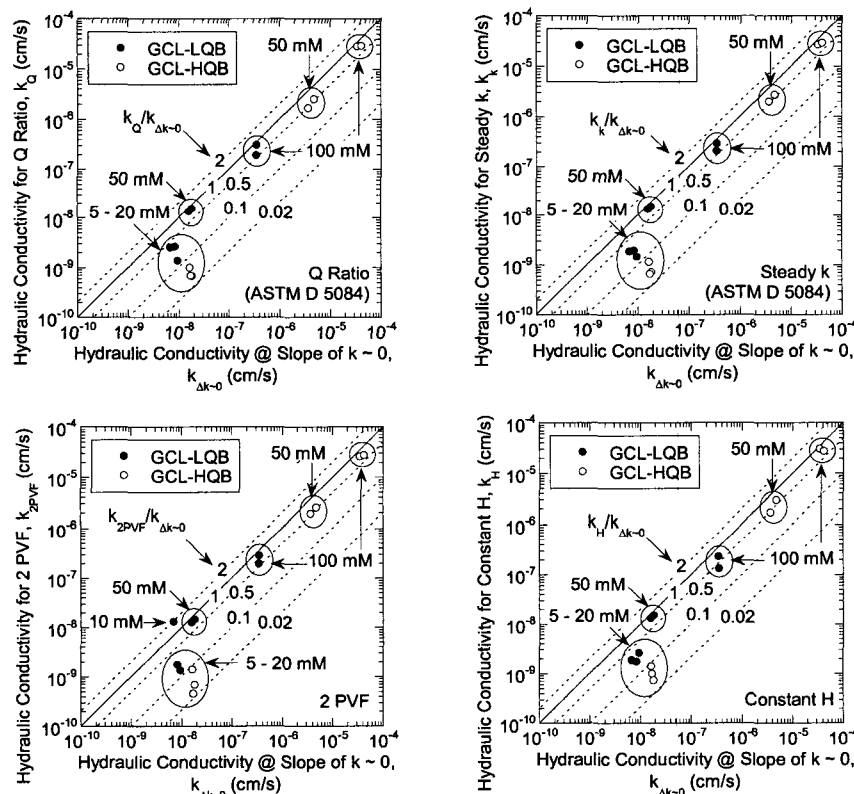


Fig. 7. Hydraulic conductivity for physical termination criteria versus hydraulic conductivity at the slope of $k \sim 0$ for non-prehydrated specimens of GCL with either lower quality bentonite (GCL-LQB) or higher quality bentonite (GCL-HQB) (Q = volumetric flow rate; PVF = pore volumes of flow; H = thickness of specimen)

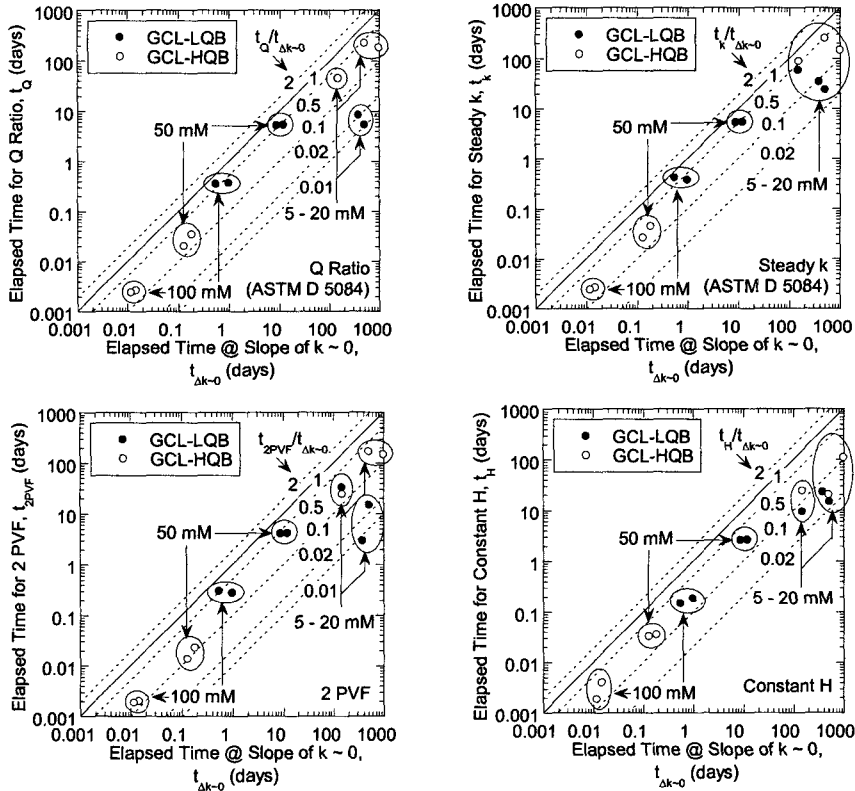


Fig. 8. Elapsed time for physical termination criteria versus elapsed time at the slope of hydraulic conductivity ~ 0 for non-prehydrated specimens of GCL with either lower quality bentonite (GCL-LQB) or higher quality bentonite (GCL-HQB) (Q = volumetric flow rate; PVF = pore volumes of flow; H = thickness of specimen)

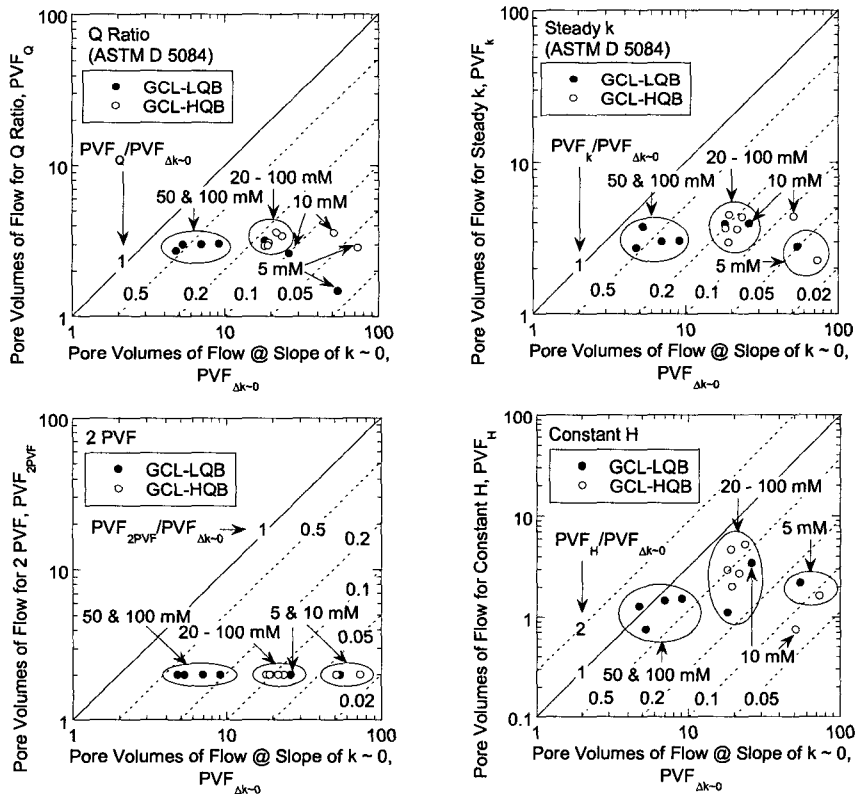


Fig. 9. Pore volumes of flow (PVF) for physical termination criteria versus PVF at the slope of hydraulic conductivity ~ 0 for non-prehydrated specimens of GCL with either lower quality bentonite (GCL-LQB) or higher quality bentonite (GCL-HQB) (Q = volumetric flow rate; H = thickness of specimen)

are from 4X to 5X for the GCL-LQB and from 11X to 25X for the GCL-HQB lower than the $k_{\Delta k \sim 0}$ values. Thus, this termination criterion also is not applicable for the tests on both GCL specimens permeated with 5, 10, and 20 mM CaCl_2 solutions.

Thus, the physical termination criteria evaluated in this study are not particularly applicable in terms of their ability to achieve equilibrium in hydraulic conductivity for the specimens of both GCLs (i.e., GCL-LQB and GCL-HQB) permeated with 5, 10, and 20 mM CaCl_2 solutions. For the specimens permeated with 50 and 100 mM CaCl_2 solutions, the hydraulic conductivity values based on overall physical termination criteria are not significantly different (i.e., < 50%) from the $k_{\Delta k \sim 0}$ values regardless of quality of bentonite used in the GCLs. Thus, any physical termination criterion appears to be adequate for both GCLs when permeated with 50 and 100 mM CaCl_2 solutions. As shown in Figs. 8 and 9, the elapsed times and PVF for the GCL-HQB required to meet the physical termination criteria generally are

greater than those for the GCL-LQB for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions, whereas the elapsed times and PVF required for the GCL-HQB specimens generally are lower than those for the GCL-LQB specimens when the specimens are permeated with 50 and 100 mM CaCl_2 solutions.

The hydraulic conductivity values based on the chemical termination criteria are compared with the $k_{\Delta k \sim 0}$ values for non-prehydrated specimens of both GCLs (i.e., GCL-LQB and GCL-HQB) in Fig. 10. The hydraulic conductivity values based on either tolerance for the EC ratio criteria (i.e., $EC_{out}/EC_{in} = 1.00 \pm 0.10$ or 1.00 ± 0.05) are always less than the $k_{\Delta k \sim 0}$ values regardless of bentonite quality for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions. In fact, the hydraulic conductivity ratios based on the EC ratio of 1.00 ± 0.10 (i.e., $k_{EC0.1}/k_{\Delta k \sim 0}$) range from 0.2 to 0.3 for the GCL-LQB and from 0.1 to 0.2 for the GCL-HQB, except for the GCL-HQB permeated with the 20 mM CaCl_2 solution, where the $k_{EC0.1}/k_{\Delta k \sim 0}$ value is about 0.6.

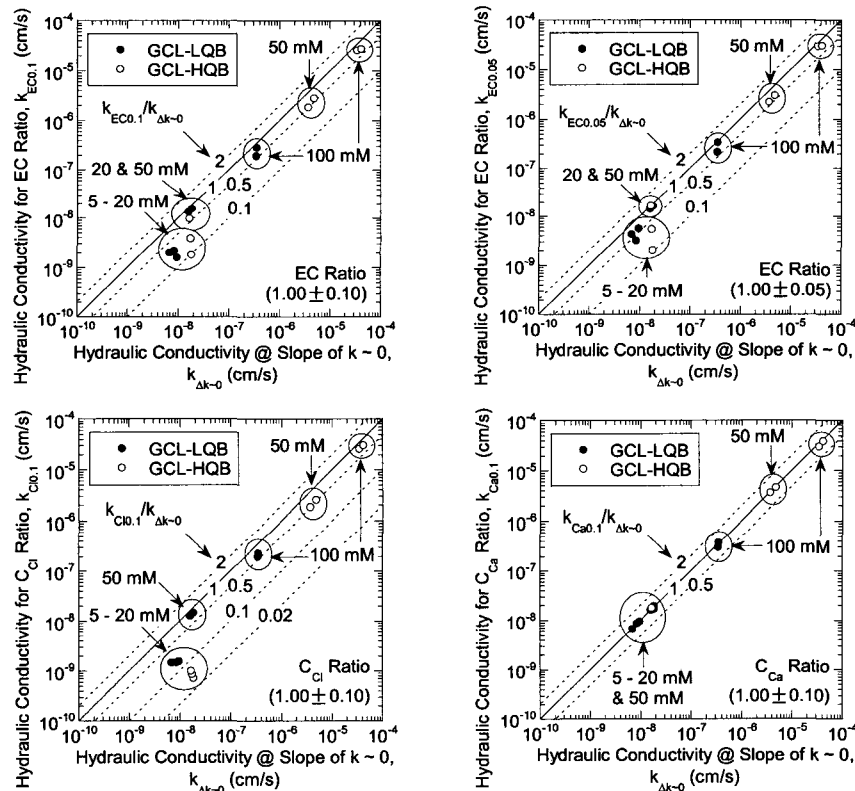


Fig. 10. Hydraulic conductivity for chemical termination criteria versus hydraulic conductivity at the slope of $k \sim 0$ for non-prehydrated specimens of GCL with either lower quality bentonite (GCL-LQB) or higher quality bentonite (GCL-HQB) (EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium)

Similarly, the hydraulic conductivity ratios based on the EC ratio of 1.00 ± 0.05 (i.e., $k_{EC0.05}/k_{\Delta k \sim 0}$) range from 0.4 to 0.6 for the GCL-LQB and from 0.1 to 0.3 for the GCL-HQB, except for the GCL-HQB permeated with the 20 mM CaCl_2 solution, where the $k_{EC0.1}/k_{\Delta k \sim 0}$ value is 1.0. Thus, chemical equilibrium between the effluent and the influent EC apparently is a necessary, but not a sufficient condition to ensure equilibrium in hydraulic conductivity regardless of bentonite quality for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions. On the other hand, for the specimens permeated with 50 and 100 mM CaCl_2 solutions, the hydraulic conductivity values based on either tolerance of the EC ratio are not significantly lower (i.e., $\leq 50\%$) than the $k_{\Delta k \sim 0}$ values for both GCLs. Therefore, the EC criteria apparently are more appropriate in terms of providing a true measure of $k_{\Delta k \sim 0}$ for the specimens of both GCLs permeated with 50 and 100 mM CaCl_2 solutions.

Similarly, the hydraulic conductivity ratios based on

the Cl^- concentration equilibrium requiring $C_{\text{Cl,out}}/C_{\text{Cl,in}} = 1.00 \pm 0.10$ (i.e., $k_{\text{Cl}0.1}/k_{\Delta k \sim 0}$) are less than 0.3 for the GCL-LQB and less than 0.1 for the GCL-HQB, which also indicates its insufficiency as a termination criterion, for the specimens of both GCLs permeated with 5, 10, and 20 mM CaCl_2 solutions. In fact, as shown in Fig. 10, $k_{\Delta k \sim 0}$ for both GCLs was only established when the Ca^{2+} concentrations in the effluent and influent were similar (i.e., $C_{\text{Ca,out}}/C_{\text{Ca,in}} = 1.00 \pm 0.10$). Thus, regardless of the quality of bentonite used in the GCLs, the chemical termination criterion based on Ca^{2+} concentration equilibrium is both necessary and sufficient to ensure the establishment of equilibrium in hydraulic conductivity based on the results for the specimens permeated with 5, 10, and 20 mM CaCl_2 solutions. As shown in Fig. 10, the hydraulic conductivity values based on either Cl^- or Ca^{2+} concentration equilibrium are not significantly lower (i.e., $\leq 50\%$) than the $k_{\Delta k \sim 0}$ values (i.e., $\leq 50\%$) for the specimens of both GCLs permeated with 50 and 100 mM CaCl_2 solutions.

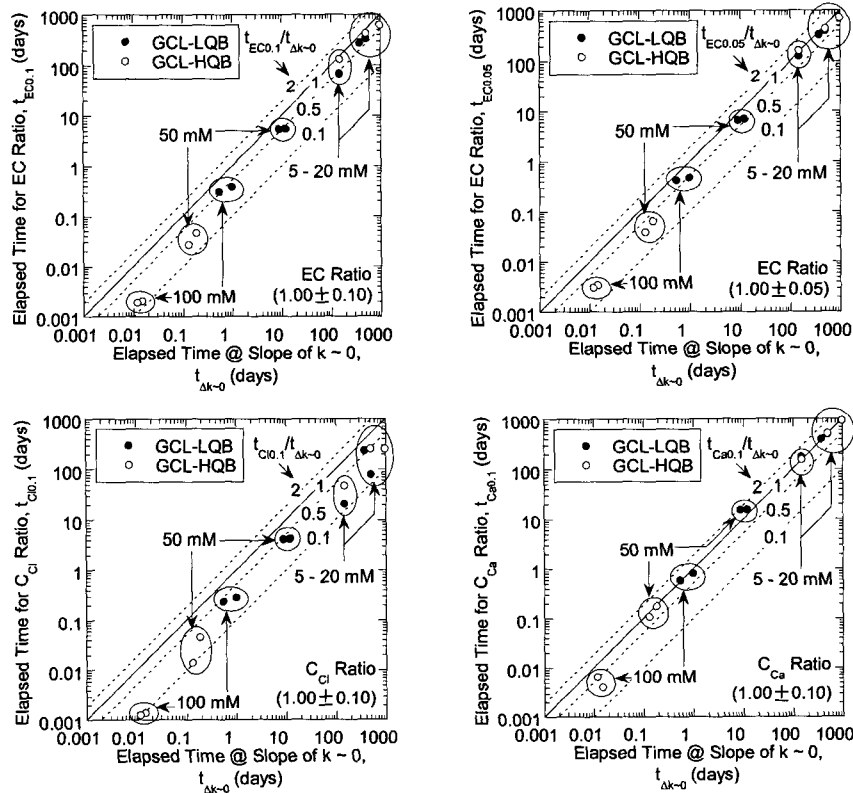


Fig. 11. Elapsed time for chemical termination criteria versus elapsed time at the slope of hydraulic conductivity ~ 0 for non-prehydrated specimens of GCL with either lower quality bentonite (GCL-LQB) or higher quality bentonite (GCL-HQB) (EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium)

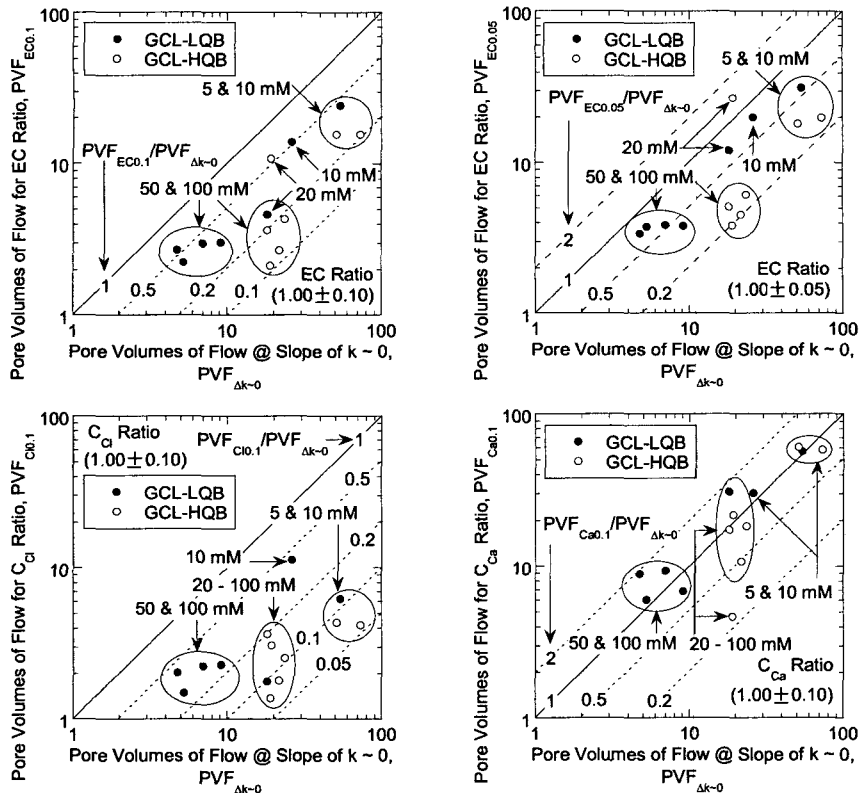


Fig. 12. Pore volumes of flow (PVF) for chemical termination criteria versus PVF at the slope of hydraulic conductivity ~ 0 for non-prehydrated specimens of GCL with either lower quality bentonite (GCL-LQB) or higher quality bentonite (GCL-HQB) (EC = electrical conductivity; C_{Cl} or C_{Ca} = concentration of chloride or calcium)

As shown in Figs. 11 and 12, the elapsed times and PVF based on the chemical termination criteria are generally greater for the GCL-HQB than for the GCL-LQB for the specimens permeated with 5, 10, and 20 mM $CaCl_2$ solutions. In contrast, the elapsed times and PVF are generally lower for the GCL-HQB than for the GCL-LQB for the specimens permeated with 50 and 100 mM $CaCl_2$ solutions.

4. Summary and Conclusions

Hydraulic conductivity tests were performed on two geosynthetic clay liners (GCLs) containing different qualities of bentonite with or without prehydration to evaluate adequacy of a wide range of termination criteria commonly used in compatibility testing of GCLs with respect to prehydration and quality of bentonite by permeating the GCL specimens with calcium chloride ($CaCl_2$) solutions. All of the hydraulic conductivity tests are not terminated before chemical equilibrium between

the influent and the effluent as well as equilibrium in hydraulic conductivity has been established. These requirements resulted in test durations ranging from < 1 day to > 900 days, with longer test durations associated with lower $CaCl_2$ concentrations. None of the physical termination criteria (i.e., volumetric flow ratio and steady hydraulic conductivity per ASTM D 5084, 2 pore volumes of flow, constant thickness of specimen) was adequate for the specimens permeated with 5, 10, and 20 mM $CaCl_2$ solutions regardless of prehydration or quality of bentonite because the equilibrium in hydraulic conductivity had not been established at the times corresponding to those criteria. On the other hand, the overall physical termination criteria tend to ensure equilibrium in hydraulic conductivity regardless of prehydration or quality of bentonite for the specimens permeated with 50 and 100 mM $CaCl_2$ solutions.

In terms of chemical termination criteria, the pH ratio (i.e., pH_{out}/pH_{in}) was never within the acceptable range (i.e., 1.00 ± 0.10) throughout any of the tests performed

in this study, except for one prehydrated GCL specimen permeated with a 100 mM CaCl₂ solution. Furthermore, the hydraulic conductivity values based on electrical conductivity (EC) equilibrium are always from 2X to 10X lower than the hydraulic conductivity values at the statistically zero slope (or $k_{Dk \sim 0}$), regardless of prehydration or quality of bentonite for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions, except for one specimen permeated with the 20 mM CaCl₂ solution. Thus, the EC equilibrium is a necessary, but not sufficient, condition to ensure equilibrium in hydraulic conductivity particularly for the specimens permeated with 5, 10, and 20 mM CaCl₂ solutions. In fact, equilibrium in hydraulic conductivity was not established until the Ca²⁺ concentrations in the effluent and influent were similar (i.e., $C_{Ca,out}/C_{Ca,in} = 1.00 \pm 0.10$), regardless of prehydration or quality of bentonite. On the other hand, any chemical termination criterion tends to ensure equilibrium in hydraulic conductivity regardless of prehydration or quality of bentonite for the specimens permeated with 50 and 100 mM CaCl₂ solutions. Thus, the termination criteria based on equilibrium in effluent and influent calcium concentration is unique so that this criteria can be used to represent the equilibrium hydraulic conductivity based on a statistically zero slope (or $k_{Dk \sim 0}$), regardless of CaCl₂ concentration, prehydration of the GCL, or quality of the bentonite in the GCL.

Acknowledgement

Financial support for this study was provided by the U. S. National Science Foundation (NSF), Arlington, VA, under Grant CMS-9820863 entitled, "Long-Term Performance of GCLs Permeated with Aqueous Inorganic Solutions". The opinions expressed in this paper are solely those of the writers and are not necessarily consistent with the policies or opinions of the NSF.

References

- Alther, G., Evans, J. C., Fang, H.-Y., and Witmer, K. (1985), "Influence of Inorganic Permeants upon the Permeability of

- Bentonite", *Hydraulic Barriers in Soil and Rock*, A. I. Johnson, R. K. Frobel, N. J. Cavalli, and C. B. Pettersson (eds.), ASTM STP 874, West Conshohocken, PA, pp.64-73.
- Bowders, J. J., Jr. (1988), "Termination Criteria for Clay Permeability Testing (Discussion)", *Journal of Geotechnical Engineering*, ASCE, Vol.114, No.8, pp.947-949.
- Bowders, J. J., Jr. and Daniel, D. E. (1987), "Hydraulic Conductivity of Compacted Clay to Dilute Organic Chemicals", *Journal of Geotechnical Engineering*, ASCE, Vol.113, No.12, pp.1432-1448.
- Bowders, J. J., Jr., Daniel, D. E., Broderick, G. P., and Liljestrand, H. M. (1986), "Methods for Testing the Compatibility of Clay Liners with Landfill Leachate", *Hazardous and Industrial Solid Waste Testing: Fourth Symposium*, J. K. Petros, Jr., W. J. Lacy, and R. A. Conway (eds.), ASTM STP 886, West Conshohocken, PA, pp.233-250.
- Daniel, D. E. (1994), "State-of-art: Laboratory Hydraulic Conductivity Tests for Saturated Soils", *Hydraulic Conductivity and Waste Contaminant Transport in Soil*, D. E. Daniel and S. J. Trautwein (eds.), ASTM STP 1142, West Conshohocken, PA, pp.30-78.
- Daniel, D. E., Bowders, J. J., Jr., and Gilbert, R. B. (1997), "Laboratory Hydraulic Conductivity Testing of GCLs in Flexible-Wall Permeameters", *Testing and Acceptance Criteria for Geosynthetic Clay Liners*, L. W. Well (ed.), ASTM STP 1308, West Conshohocken, pp.208-226.
- Daniel, D. E., Shan, H.-Y., and Anderson, J. D. (1993), "Effects of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner", *Geosynthetics '93*, Industrial Fabrics Association International, St. Paul, MN, Vol.3, pp.1483-1496.
- Didier, G. and Comeaga, L. (1997), "Influence of Initial Hydration Conditions on GCL Leachate Permeability", *Testing and Acceptance Criteria for Geosynthetic Clay Liners*, L. W. Well (ed.), ASTM STP 1308, West Conshohocken, PA, pp.181-195.
- Dobras, T. N. and Elzea, J. M. (1993), "In-Situ Soda Ash Treatment for Contaminated Geosynthetic Clay Liners", *Geosynthetics '93*, Industrial Fabrics Association International, St. Paul, MN, Vol.3, pp.1145-1160.
- Egloffstein, T. (2001), "Natural Bentonites - Influence of the Ion Exchange and Partial Desiccation on Permeability and Self-Healing Capacity of Bentonites used in GCLs", *Geotextiles and Geomembranes*, Vol.19, No.7, pp.427-444.
- Gleason, M. H., Daniel, D. E., and Eykholt, G. R. (1997), "Calcium and Sodium Bentonite for Hydraulic Containment Applications", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.123, No.5, pp.438-445.
- Imamura, S., Sueoka, T., and Kamon, M. (1996), "Long Term Stability of Bentonite/Sand Mixtures at L.L.R.W. Storage", *Environmental Geotechnics*, M. Kamon (ed.), A. A. Balkema, Rotterdam, Vol.1, pp.545-550.
- James, A. N., Fullerton, D., and Drake, R. (1997), "Field Performance of GCL under Ion Exchange Conditions", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.123, No.10, pp.897-902.
- Jo, H. Y., Katsumi, T., Benson, C. H., and Edil, T. B. (2001), "Hydraulic Conductivity and Swelling of Nonprehydrated GCLs Permeated with Single-Species Salt Solutions", *Journal of*

- Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.127, No.7, pp.557-567.
15. Kolstad, D. C. (2000), *Compatibility of Geosynthetic Clay Liners (GCLs) with Multi-Species Inorganic Solutions*, M.S. Thesis, University of Wisconsin at Madison, WI, 167 p.
 16. Lee, J.-M. (2004), *Long-Term Hydraulic Performance of Geosynthetic Clay Liners Subjected to Inorganic Salt Solutions*, Ph.D. Dissertation, Colorado State University, Fort Collins, CO, 402 p.
 17. Lee, J.-M. and Shackelford, C. D. (2005a), "Concentration Dependency of the Prehydration Effect for a Geosynthetic Clay Liner", *Soils and Foundations*, Japanese Geotechnical Society, in review.
 18. Lee, J.-M. and Shackelford, C. D. (2005b), "Impact of Bentonite Quality on Hydraulic Conductivity of Geosynthetic Clay Liners", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, in press.
 19. Lin, L.-C. and Benson, C. H. (2000), "Effect of Wet-Dry Cycling of Swelling and Hydraulic Conductivity of GCLs", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.126, No.1, pp.40-49.
 20. Melchior, S. (1997), "In-Situ Studies on the Performance of Landfill Caps (compacted clay liners, geomembranes, geosynthetic clay liners, capillary barriers)", *Proceedings, International Containment Conference*, St. Petersburg, FL, pp.365-373.
 21. Peirce, J. J. and Witter, K. A. (1986), "Termination Criteria for Clay Permeability Testing", *Journal of Geotechnical Engineering*, ASCE, Vol.112, No.9, pp.841-854.
 22. Petrov, R. J. and Rowe, R. K. (1997), "Geosynthetic Clay Liner (GCL) - Chemical Compatibility by Hydraulic Conductivity: Testing and Factors Impacting its Performance", *Canadian Geotechnical Journal*, Vol.34, No.6, pp.863-885.
 23. Petrov, R. J., Rowe, R. K., and Quigley, R. M. (1997a), "Comparison of Laboratory-Measured GCL Hydraulic Conductivity Based on Three Permeameter Types", *Geotechnical Testing Journal*, ASTM, Vol.20, No.1, pp.49-62.
 24. Petrov, R. J., Rowe, R. K., and Quigley, R. M. (1997b), "Selected Factors Influencing GCL Hydraulic Conductivity", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.123, No.8, pp.683-695.
 25. Quaranta, J. D., Gabr, M. A., and Bowders, J. J., Jr. (1997), "First-Exposure Performance of the Bentonite Component of a GCL in a Low-pH, Calcium-Enriched Environment", *Testing and Acceptance Criteria for Geosynthetic Clay Liners*, L. W. Well (ed.), ASTM STP 1308, West Conshohocken, PA, pp.162-180.
 26. Ruhl, J. L. and Daniel, D. E. (1997), "Geosynthetic Clay Liners Permeated with Chemical Solutions and Leachates", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.123, No.4, pp.369-381.
 27. Shackelford, C. D. (1994), "Waste-Soil Interactions that Alter Hydraulic Conductivity", *Hydraulic Conductivity and Waste Contaminant Transport in Soil*, D. E. Daniel and S. J. Trautwein (eds.), ASTM STP 1142, West Conshohocken, PA, pp.111-168.
 28. Shackelford, C. D., Benson, C. H., Katsumi, T., Edil, T. B., and Lin, L. (2000), "Evaluation the Hydraulic Conductivity of GCLs Permeated with Non-Standard Liquids", *Geotextiles and Geomembranes*, Vol.18, No.2-4, pp.133-161.
 29. Shan, H.-Y. and Daniel, D. E. (1991), "Results of Laboratory Tests on a Geotextile/Bentonite Liner Material", *Geosynthetics '91*, Industrial Fabrics Association International, St. Paul, MN, Vol.2, pp.517-535.
 30. Shan, H.-Y. and Lai, Y.-J. (2002), "Effect of Hydrating Liquid on the Hydraulic Properties of Geosynthetic Clay Liners", *Geotextiles and Geomembranes*, Vol.20, No.1, pp.19-38.
 31. Stern, R. T. and Shackelford, C. D. (1998), "Permeation of Sand-Processed Clay Mixtures with Calcium Chloride Solutions", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.124, No.3, pp.231-241.
 32. Vasko, S. M., Jo, H. Y., Benson, C. H., Edil, T. B., and Katsumi, T. (2001), "Hydraulic Conductivity of Partially Prehydrated Geosynthetic Clay Liners Permeated with Aqueous Calcium Chloride Solutions", *Proceedings, Geosynthetics '01*, St. Paul, MN, pp.685-699.

(received on Aug. 2, 2004, accepted on Sep. 15, 2004)